

# What have we learned and want to learn from heavy ion collisions at CERN SPS?

E.V. Shuryak<sup>a</sup>

<sup>a</sup>State University of New York, Stony Brook, NY 11794, USA

The talk is a mini-review of the current status of the field, with emphasis on SPS heavy ion program, now and beyond 2000 (as asked by the organizers). The main question is, of course, whether we can convince ourselves and the community at large that the QGP is in fact produced at SPS. We came a long way toward the *positive* answer, and are definitely on strongly rising part of the learning curve. Still, in few key directions we lack important pieces of evidences.

## 1. The QCD Phase Diagram

### 1.1. Theoretical progress

The QCD phase diagram version circa 1999 [1], shown in Fig 1(a), looks rather different from what was shown at previous Quark Matter conferences. Most significant progress is seen in the large-density low-T region, where two new Color Super-conducting phases have appeared. Unfortunately heavy ion collisions do not cross this part of the phase diagrams: it belongs to neutron star physics.

The subject is covered in talks [2], so I only make few comments here. The 2-flavor-like color superconductor CSC2 phase was known before [3], but realization that it should be induced by instantons [4] has increased the gaps (and  $T_c$ ) from a few MeV scale to  $\sim 100$  MeV (50 MeV). It is hardly surprising, since the *same* interaction in  $\bar{q}q$  channel is responsible for chiral symmetry breaking, with the gap (a constituent quark mass) 350-400 MeV. The symmetries of the CSC2 phase are similar to the electroweak part of the Standard Model, with scalar isoscalar  $ud$  diquark as Higgs. The colored condensate breaks the color group, making 5 out of 8 gluons massive. The 3-flavor-like phase, CSC3, is brand new: it was proposed in [5] based on one gluon exchange interaction, but in fact it is favored by instantons as well [1]. Its unusual features include *color-flavor locking* and *coexistence* of both types of condensates,  $\langle qq \rangle$  and  $\langle \bar{q}q \rangle$ . It combines features of the Higgs phase (8 massive gluons) and of the usual hadronic phase (8 massless “pions”). Surprisingly, at very large densities Cooper pairs are bound magnetically [6], leading to growing gaps at extremely large  $\mu$ .

Another important new element is the (remnant of) the QCD tricritical point [7]. Although we do not know where it is<sup>1</sup>, we hope we know how to find it, see [7]. All ideas proposed rotate around the fact that the order parameter, the famous sigma meson, is at

<sup>1</sup>Its position is very sensitive to precise value of the strange quark mass  $m_s$

this point truly massless, and creates a kind of a “critical opalecence”.

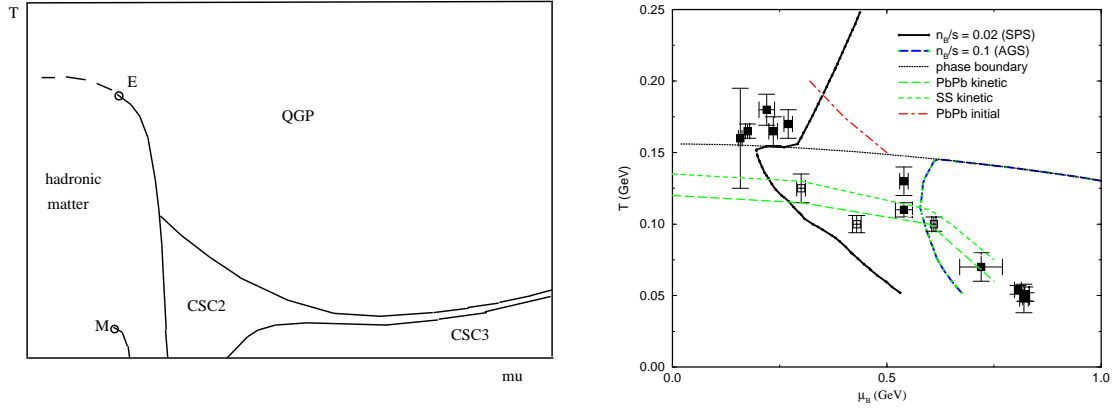


Figure 1. (a) Schematic phase diagram of QCD, in temperature  $T$ - baryon chemical potential  $\mu$  plane.  $E$  and  $M$  show critical endpoints of first order transitions:  $M$  (from multi-fragmentation) is that for liquid-gas transition in nuclear matter. The color superconducting phases, CSC2 and CSC3 are explained in the text. (b) The experimentally accessible part of the phase diagram. Closed (open) points correspond to chemical (thermal) freeze-out (from analysis compiled in [8]) The adiabatic paths correspond to entropy per baryon ratio indicated, from [16] . Lines of thermal freeze-out for central SS and PbPb collisions, as well as the initial line for PbPb are also indicated.

## 1.2. The Phase diagram as our Map

The major goal of the heavy ion program in general is to reproduce as much as possible properties of dense/hot matter in bulk, and study qualitatively new phenomena like phase transitions. Now, with accurate statistical description of the particle composition, small and Gaussian event-by-event (EBE) fluctuations, and detailed data on collective flow, people are using macroscopic language more than before, and so it is entirely appropriate to start with a discussion of *where we are on the phase diagram*.

Looking at the fireball by a detector is like looking at the Sun: one can only see the photo-sphere, with  $T \sim 6000^\circ$ , not the hotter interior. Because we can see many hadronic species, we can also trace down conditions at which the composition is formed. The result can be summarized as two separate freeze-out points, *thermal* or kinetic one, and *chemical*: a recent sample of those coming from SPS, AGS and SIS data is shown in Fig.1(b). The chemical point are about the same for all  $A$ , but the thermal ones are “cooler” for larger  $A$ . For a discussion of freeze-out systematics see [8]. Only at SPS we find that the two freeze-outs are well separated, and so we indeed found a new phase of matter at SPS, never seen before: namely a *chemically frozen thermally equilibrated “resonance” gas*.

The zigzag shaped paths on the phase diagram are *adiabatic curves* for a particular EOS [16](b) which I have discussed at QM97 [16](c): one can see that measured freeze-out points at SPS and AGS happen to be close to the predicted paths. Do chemical and thermal points indeed follow the same adiabates of “resonance gas”? The points in Fig.1(b) are not accurate enough to say that, but it can be studied in models. In

[9] the URQMD cascade was studied<sup>2</sup>, and although the non-equilibrium effects in some observables can be large, the exact and equilibrium expressions for entropy differ by only about 6%. Also the kinetic models agree that most of the entropy is produced early, and then it is only slightly affected by re-scattering. In summary: the adiabatic paths seem to be the paths to follow!

## 2. Hadronic stage

### 2.1. The radial flow

The main news from the last few years is that at AGS/SPS energy domain the heavy ion collisions really produce a *Little Bang rather than a fizzle*, with strong explosive transverse flow converting a significant part of thermal energy into that of collective motion.

Looking two decades ago at the pp ISR data I have found [15] no trace of transverse radial flow: the  $m_t$  slopes for various secondaries were identical. Only in mid-90s a significant difference in slopes was observed, first for light- and then heavy-ion collisions. At all previous QM conferences the origin of these slopes was debated. Are differences in AA and pp due to “initial state” parton re-scattering or the final state re-scattering of hadrons? Now the debate is mostly over since the amount of evidences which proves the latter is overwhelming. Let me mention two of them. (i) Initial state scattering may broaden the nucleon  $m_t$  spectra, but it then predicts *the same* slope for deuterons, contrary to observations. Only a correlation between the two nucleons can explain data, and the calculated flow reproduces it well[17]. (ii) slopes for  $\pi, K, N, d$  depend linearly on particle mass (common flow velocity  $v_t$ ), except for strange baryons. The largest deviation is found for  $\Omega^-$ : this is nicely explained [18] by its early freeze-out due to smaller cross sections<sup>3</sup>.

How large is the transverse flow velocity  $v_t$ ? The fits to “hydro-motivated” formulae have produced widely varying values, which also were strongly A- and rapidity dependent. The explanation was worked out in the hydro-kinetic framework [16], which I also described at QM97. The *motto* of this work, “the larger the system, the further it cools”, explains both strong A and y dependence of flow. Very large  $v_t \approx .6$  and very low  $T_{thermal} = 110 - 120 MeV$  in PbPb were predicted<sup>4</sup>. Later analysis based heavily on NA44, NA49 **HBt radii and spectra** have confirmed such selection [10].

The value of  $v_t$  is important because it *tells us about the EOS of hadronic matter*. The observed values are mostly generated by “resonance gas”, which at SPS has simple EOS [19]  $p \approx .2\epsilon$ ,  $p, \epsilon \sim T^6$ .  $v_t$  is large because “resonance gas” at  $T = 120 - 160 MeV$  has no Hagedorn “softening”<sup>5</sup>. The mixed phase is however softer, with the minimum of  $p/\epsilon$  (the *the softest point*) corresponding to all matter converted to QGP. It was predicted [16](a) that the collisions which start from this condition should last longer. We are waiting for

<sup>2</sup>This model of course has no zigzag and QGP, only the hadronic part of the path is the same.

<sup>3</sup>Why does the  $\phi$  not have a small slope as well? See discussion below.

<sup>4</sup>As only very elementary kinetics of low energy pion and nucleon re-scattering is actually involved, any event generator like RQMD also “knew” about it. Just it was not put in the proper words.

<sup>5</sup>The Hagedorn phenomenon caused by the exponential rise of spectral density was in fact found to exist in QCD without quarks. It accurately explains lattice data on the value of the deconfinement transition for  $N_c = 2, 3, 4$ . So, the Hagedorn softening would have happened in QCD at  $T_{Hagedorn} \approx 260 MeV$ , if not for the light-quark dominated transition at lower T.

the next SPS run, at 40 GeV, to see if this prediction is indeed confirmed.

## 2.2. Elliptic flow

In high energy collisions the shape of the “initial almond” for non-central collisions leads to enhanced “in-plane” flow, in the direction of the impact parameter [20]. It is very important because (as pointed out in [21](a)) it is developed *earlier* than the radial one, and thus it may shed light on whether we do or do not have QGP at such time. Now it is measured by the asymmetry of the particle *number*, or  $v_i$  harmonics defined as  $\frac{dN}{d\phi} = \frac{v_0}{2\pi} + \frac{v_2}{\pi} \cos(2\phi) + \frac{v_4}{\pi} \cos(4\phi) + \dots$  rather than asymmetry of the momentum distribution. Furthermore,  $v_i$  can be additionally normalized to the spatial asymmetry of the initial state (the “almond”) at the same  $b$ , in order to cancel out this kinematic factor and to see the response to asymmetry.

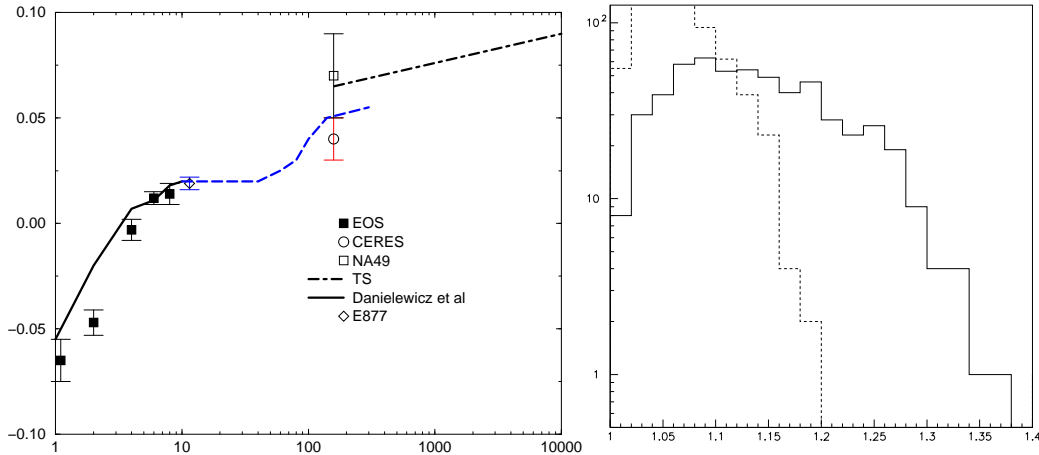


Figure 2. Nucleon ellipticity  $v_2$  at mid-rapidity and mid-central collisions, versus collision energy [GeV/N]. The experimental sources are (compiled in [25]) and indicated on figure, TS is hydro calculation [26], the dashed line is just a guess (see text). (b) Distribution of the ratio of long-to-short r.m.s. radii of the participant nuclei in transverse direction, for large number of participants  $N_p > .9N_{max}$ . Solid (dashed) histogram is for UU (PbPb) collisions.

Let us first look at the energy dependence: a compilation of measured nucleon  $v_2$  is shown in Fig.2(a). First news is indication for **softening of EOS** at  $E > 6A\text{GeV}$  observed by EOS detector at AGS, exactly where the initial conditions are expected to hit for the first time the critical line (see [22]). At the same energy  $K/\pi$  ratio and other strangeness enhancement signals change rapidly. Both indicate that the mixed phase is actually reached *already at such low energies*.

The dash-dotted curve for energies above the SPS is from hydro calculations [26]. In agreement with [20], large and near constant ellipticity in this region is found, driven by *the QGP push* at early times. Strong decrease of this effect is expected in the SPS domain, as the “QGP push” disappears. The dashed curve is my speculation of what the excitation function of  $v_2$  may be in the SPS domain. The existence of a *plateau* is not

obvious, but an **inflection point** seems inevitable<sup>6</sup>.

Let us now turn to SPS data, which depict *centrality* dependence of  $v_2$ . This issue is more complicated, because by increasing  $b$  we make the “almond” more elliptic, but also much smaller and thinner: eventually finite size corrections reduce the pressure build-up<sup>7</sup>. One needs cascade codes to study this effect: see [21]. Last year RQMD has been radically changed, including the possibility to vary the EOS and to include the “QGP push”. New version [21](b) predicts a relative growth of (properly normalized to spatial asymmetry)  $v_2$  at small  $b$ , to values close to those predicted by hydro. Preliminary NA49 data presented at this meeting [24] indeed observe such enhancement at small  $b$ .

Much more work is clearly needed to understand this complex interplay of EOS and finite size effects. U collisions discussed below in principle provide the means to decouple finite size and deformation issues. The next run (40 AGeV) data are also of great importance here: no “QGP push” is expected there. If a clear difference in  $v_2(b)$  between 40 and 158 GeV is observed, it would really be the first sign of *the QGP push* at SPS.

Whether it is seen at SPS or not, it certainly is expected to lead to quite dramatic phenomena at RHIC. A very non-trivial and highly EOS-sensitive expansion pattern is predicted in [26]: The so called “nutcracker” scenario (for non-central collisions) includes formation of two “shells”, which are physically separated from each other by freeze-out, with only a small “nut” at the center. This behavior predicts higher moments  $v_4, v_6$  of specific kind growing with energy, and spectacular HBT radii. We are looking forward to first RHIC data to see if this is true.

### 2.3. The event-by-event fluctuations: all events are (about) equal!

Search for “unusual” events (e.g. disoriented chiral condensate) had attracted significant attention in the past, but they were not found. NA49 has shown that fluctuations in such observables as  $\langle p_t \rangle$  are rather small and Gaussian, without unusual tails. Their widths can be measured rather accurately. What can we learn from them?

It is tempting to apply thermodynamical approach based on entropy here<sup>8</sup>. Furthermore, as the temperature fluctuation is related to specific heat  $\Delta T^2/T^2 = 1/C_v$ , it was proposed in [12] to use it to measure  $C_v$  of a hadronic matter at freeze-out. For example, at the critical point mentioned above,  $C_v$  diverges and  $\Delta T$  must vanish. Can this dramatic prediction be somehow observed? Unfortunately, as explained in [7], this argument is too naive. Pions can indeed be used as a “thermometer”, in contact with a fluctuating medium (the sigmas), but fluctuations of its T measures mostly the *thermometer’s own*  $C_v$ . The critical fluctuations can be seen, but only as a correction at the 10% level or so.

The fluctuations for intensive and extensive observables are generally of different nature. An example of the former case is  $\langle p_t \rangle$ : the deviation of the measured width from

---

<sup>6</sup> This prediction looks similar to that made by van Hove [23] for radial flow. His argument was however too naive, because it ignored time development: soft EOS leads to longer expansion time. Therefore even larger velocity can be obtained by the end. But ellipticity is a small effect which does *not* determine the expansion time: so in this case the argument should be valid.

<sup>7</sup> And this is why the guessed dashed curve in Fig.2(a) is below the hydro prediction.

<sup>8</sup> Such type of analysis of multi-hadron production reactions goes back to 70’s, see e.g. my own work [11] where probabilities of exclusive channels for low energy  $\bar{p}p$  annihilation were calculated from ideal gas entropy.

pure statistics (mixed events) is in this case surprisingly small<sup>9</sup>. Fluctuations of particle composition [14] are also intensive, and they are sensitive to resonances. New point: if one would be able to get any hold on multiple production of multi-strange objects, one can tell if such exotic objects as “color ropes” do or do not exist.

An example of an extensive variable is total multiplicity: even restricted to central 5% NA49 finds a Gaussian width *twice* that for random (Poisson) emission. As shown in [7], only about half of the effect comes from resonances at freeze-out. The rest must come from fluctuations in initial conditions: see discussion in [13]. I think the most interesting part of the development is attention to mixture of the two, such as  $\langle \Delta p_t \Delta N \rangle$ . As explained in [7], those do not appear in simple statistics, and so carry non-trivial information.

### 3. The initial (or pre-hadronic) stage

#### 3.1. Two main scenarios

Although we have now reached some understanding of the **hadronic stage** of the evolution, from chemical to kinetic freeze-out, we know very little about *what happens before it*. Ignoring details<sup>10</sup>, let me emphasize two major points of view present on the market: (i) **The QGP scenario** (hopefully our future Standard Model), based on a picture of quick matter equilibration; and (ii) **string scenario**, represented by most traditional Lund-type event generators like Venus and RQMD, or region-based approaches like DPM. A positive feature of the former approach is obviously its conceptual simplicity, while the latter has direct connection to pp and pA phenomenology. *Both* can explain why the initial EOS is soft enough not to contribute much to the radial flow.

**Particle composition** would be a stronghold of thermodynamics, if not for the fact that in pp and  $e^+e^-$  collisions it is also possible to use successfully statistical models. The difference is however seen in the **strangeness** production, much suppressed in pp and  $e^+e^-$  but not in AA<sup>11</sup>. The QGP scenario explains it naturally, while the string one needs “color ropes” (or other exotic devices) to explain the strangeness.

Significant experimental efforts have been made to locate the transition between two extremes, the pp-type and heavy-ion-type regimes of strangeness production. Excellent data from WA97, NA49 for  $\Lambda, \Xi, \Omega$  and their anti-particles found that strangeness has *little dependence on centrality*. Lighter ion data obtained before also confirm the impression that strangeness production is *basically constant* throughout the SPS domain, with the transition being somewhere in the AGS domain. To me it indicates that strangeness “un-suppression” is clearly related with the approach of the hadronic phase boundary, production of the mixed phase with at least *some* QGP.

We will separately discuss  $\rho$  melting and  $J/\psi$  suppression below: but let me now emphasize their contrasting A dependence. CERES data on dilepton enhancement below  $\rho$  show comparable effect in SAu and PbAu, while the NA50  $J/\psi$  suppression is drastically different. Why is it so? It is a must to see if the energy dependence of two effects is

<sup>9</sup>Even Bose enhancement which definitely is there in HBT measurements is canceled out.

<sup>10</sup> E.g. disregarding purely hadronic models, because particle composition cannot be explained by reactions in hadronic phase.

<sup>11</sup> Some studies [27] even find that strangeness is slightly enhanced compared to the equilibrium value, partly due to Coulomb effects.

different as well.

By adding  $\psi'$  in between, and decomposing  $J/\psi$  into  $\chi$  and proper  $J/\psi$  parts, one would get a whole sequence of “melting” phenomena, happening as matter becomes hotter/denser. We will see at RHIC how members of the  $\Upsilon$  family do the same later on. Which of them is the QGP signal then? Well, this depends on details which we still have to work out.

### 3.2. Dileptons

As “penetrating probes” [28], dileptons suppose to tell us the story of “melting” of all vector mesons ( $\rho, \omega, \phi, J/\psi, \Upsilon$ ), replaced by radiation from thermal quarks. All SPS dilepton experiments (HELIOS-3, CERES, NA50) see significant dilepton enhancement (compared to “trivial sources”), being stronger at small  $p_t$ , indicating matter effects.

The first important issue is the origin of the enhancement observed by NA50 at  $M_{\mu^+\mu^-} \sim 2\text{GeV}$ . It was suggested that it is due to *enhanced charm production*, but another (and, in my mind, much more probable) explanation is the *thermal QGP emission* [28]. The QGP-like rate reproduces HELIOS3 data [33], and preliminary estimates [30] show it works for NA50 data as well.

The origin of a qualitative change of the shape of the vector spectral density  $\rho_v(M)$  for  $M < 1\text{GeV}$  observed by CERES was discussed here in detail [29], let me therefore address only one central question: to what extent does the observed “ $\rho$  melting” indicate an approach to chiral symmetry restoration?

In-matter  $\rho$  width is significantly increased, mostly by re-scattering on nucleons. The non-trivial fact is: even for small masses  $M = .3 - .6\text{GeV}$  the rate (obtained in a complicated hadronic calculation [29]) happen to be rather close to the “partonic” or QGP rate, corresponding to free  $\bar{q}q$  annihilation in the heat bath. It tells us that the interaction between  $\bar{q}$  and  $q$  in the vector channel is becoming weak. *If* axial spectral density is modified similarly as well, the finite-T Weinberg-like sum rules [31] demand that the chirally-odd quantities in its r.h.s. become small, which means chiral symmetry restoration. *If* the axial spectral density remains different, chiral symmetry is still broken. Although we cannot access it directly, one may still look for Dalitz-type decays of  $a_1$  [32].

### 3.3. $J/\psi, \psi'$ suppression

Let me start with a brief comment on the  $\psi'$  suppression. The NA50 data show that the  $\psi'/\psi$  ratio stop falling and is stabilized at a small value, about 4%. An explanation suggested in [36] is: all  $\psi'$  are killed first, but then are re-created from  $J/\psi$ .

The central NA50 finding is of course a statement that  $J/\psi$  suppression for central ( $b < 8\text{ fm}$ ) PbPb collisions is different from extrapolations based on pA and SA collisions. Several mechanisms of this suppression were proposed: (i) gluonic photo-effect [28,37]; (ii) these states simply do not exist in QGP due to Debye screening [38]; (iii) hadronic co-movers kill them [39]; (iv) non-monotonous variation of the QGP lifetime, due to the “softest point” [40].

New data reported at this meeting have clarified the situation for the most central collisions: using now a very thin target, it was found that the 1996 data suffered from multiple interactions. In fact there is a significantly stronger suppression at small  $b$ ,

making the two component picture with separate  $\chi$  and  $\psi$  thresholds more probable<sup>12</sup>. It is desirable to make another step, increasing the density and/or the famous variable  $L$ : only deformed  $U$  provides an opportunity here.

What else can be done to discriminate experimentally these ideas? In particular, how can we tell whether suppression happened quickly or took a longer time? The old idea is to study suppression dependence on  $p_t$ . Unfortunately changing  $p_t$  we also change the kinematics: e.g. destruction by gluons or hadrons goes better if  $p_t$  grows.

Maybe a better idea [41] is to use the azimuthal dependence of the suppression. Instantaneous suppression should show *no* asymmetry, but if it takes a few fm/c the anisotropy should show up. The problem is the initial “almond” at  $b < 8$  fm is not very anisotropic, and for larger  $b$  there is no anomalous suppression. (Here too the deformed  $U$  can help.)

### 3.4. $\phi$ -related puzzles

$\phi$  is a little brother of  $J/\psi$ , but its production in AA is *enhanced* rather than suppressed, as compared to NN. Whatever effects are killing  $J/\psi$ 's,  $\phi$  is re-created because strangeness is close to equilibrium at chemical freeze-out.

The first puzzle is the *apparent absence of  $\phi$  in-matter modification*. As argued [34], even modest modification of kaons should strongly (by factor 2 or so) increase the width of  $\phi$  decay inside the fireball. Non-negligible fraction of  $\phi$ , up to a half, should decay in-matter, while experimentally (see e.g. excellent NA49 data presented here by C.Hohne) *no*  $\phi$  modification is seen at all!

The second puzzle (already mentioned in the flow section) is that the  $m_t$  slopes of  $\phi$  spectra measured by NA49 in KK channel are large, close to those of the  $p, \bar{p}$  (particles of similar mass). It suggests that somehow  $\phi$  participates fully in the radial flow<sup>13</sup>. How is it possible, with its small re-scattering cross section? New NA50 data on  $\phi$  reported at this conference[35] have a different slope than NA49, only about 220 MeV. If extrapolated from larger  $p_t$  (where NA50 data are) to small ones, they go well above the NA49 ones.

All puzzles may be explained if absorption destroy  $K$  from most in-matter decays<sup>14</sup>, more so at low  $p_t$ . Obviously, there should be no missing  $\phi$  in dilepton channel, and so such experiments should see the  $\phi$  missing from KK channel at low  $p_t$ . (Phenix at RHIC will have good resolution in both channels, so it should eventually clarify the issue.)

In summary: as a first (indirect) sign of missing (modified?)  $\phi$  we have evidences for the unusual change of its  $m_t$  slope. If able to cover smaller  $p_t$ , NA50 should see  $\phi$  spectra which are *different* from NA49, including those which decay inside the fireball.

## 4. Conclusions and suggestions

### 4.1. Little Bang versus the Big one

It is always fun to notice parallels to cosmology. There are many methodic similarities, as well as amusingly close timing of some recent developments.

The first obvious connection between the “Little Bangs” in AA collisions and the “Big Bang” is that both are violent explosions. Expansion of the created hadronic fireball

<sup>12</sup>And the idea (iv), according to which suppression may even become weaker at smaller  $b$  less likely.

<sup>13</sup>Again, ellipticity may give a clue here.

<sup>14</sup>Or their *refraction* in a collective potential.



approximately follows the Hubble law,  $v \sim r$ , although anisotropic one. The *final* velocities, the Hubble constant and  $v_t$ , have been a matter of debates few years ago, but now are believed to be fixed (at say 10% level). The next important issue in both cases is the *acceleration history*, needed to shed some light on the fundamental EOS. Cosmologists use distant supernovae to access flow long ago: we use  $\Omega^-$  to learn what was the flow at “mid-time” (5-10 fm/c).

The last point: angular anisotropy of flow and its fluctuations. Amazingly accurate measurements of the microwave background have found a dipole anisotropy (due to our motion relative to “ether”) and tiny ( $\sim 10^{-5}$ ) fluctuations with angular momentum  $l \sim 100$  due to frozen plasma oscillations, from the freeze-out stage in which the QED plasma was neutralized into ordinary atomic matter. In the Little Bang we have *average* dipole and elliptic flows of a few percent. *Fluctuating* higher harmonics are not analyzed yet: there must be some trace of “frozen QGP oscillations” as well. True, cosmologists have much more photons, but they are restricted to *only one event*, while we have millions of them!

#### 4.2. Using deformed nuclei (U): An old idea with a new twist

An old idea<sup>15</sup> is to select head-on (long-long) collisions, by triggering on maximal number of participants  $N_p$ . Because of larger A and *deformation*, the gain in energy density can realistically reach 35-40% [42], which is important e.g. for the  $J/\psi$  suppression studies.

The main finding of my recent studies of UU collisions [42] is however a possible virtue of “parallel” collisions, in which both long axis are orthogonal to the beam. Using *two* control parameters, the number of participants and ellipticity<sup>16</sup>, one can effectively separate those. As one can see from Fig.2(b), unlike PbPb collisions, the UU ones provide a range of deformations, with long-to-short ratio reaching about 1.3. (Those correspond to collisions with two long directions parallel to each other and orthogonal to the beam). It is comparable to the deformation reached for mid-central collisions of spherical nuclei, but now for much larger and denser system.

As mentioned several times in this talk, it may help to clarify many issues, such as presence of the QGP push in elliptic flow at SPS, a time scale of the  $J/\psi$  suppression, etc. One more example are corrections to hard processes, like “shadowing” due to initial state re-scattering or “jet quenching” due to final state. Selecting two geometries, head-to-head and “parallel”, one can change the longitudinal to transverse size ratio from 1.3 to 1/1.3, a significant level arm to tell the difference.

#### 4.3. Experimental goals

It is clear that there can only be a finite time-span for the SPS heavy ion program, so we have to be “picky”. I think the following list includes only experiments which are a complete “must”.

---

<sup>15</sup>Kind of a folklore of our field, the only written version I found is a memo written by P.Braun-Munzinger to BNL.

<sup>16</sup>The measured deformation of spectra,  $v_2$ , is proportional to this initial deformation (with EOS-depending coefficient!) and should have similar distribution.

- – It is not likely this energy region would be studied later, so we better be sure no qualitative phenomenon is missed. For years I advocated measuring SPS excitation function looking for the “softest point”, and we will have the 40 GeV run soon. Now excitation function of  $v_2$  became an important issue, with a potential to see “the QGP push” at SPS. Another compelling argument for a scan is hunting for the tricritical point of QCD: finding it would be a major breakthrough, going to textbooks etc.
- – The nature of the dilepton excess for  $M \sim 2\text{GeV}$  found by NA50 should be understood. If it is indeed charm enhancement, up to factor 3 for central PbPb, then the  $J/\psi$  suppression issue is much more serious. If it is QGP radiation, it should be studied more. The number one hadronic measurements which remains to be done is therefore *direct observation of charm* by D’s.
- –  $J/\psi$  suppression is high priority, as the only observable in which relatively sharp centrality dependence. By changing the beam (A, collision energy) one should test whether the variation seen is or is not related to fixed energy density. Time-scale of the suppression can be accessed by studying its  $p_t$  dependence or “ellipticity”.
- – CERES: significant improvement of signal/background ratio is expected from its recent upgrade, leading to clear separation of the  $\omega$  from the  $\rho$  peak, as well as independent look at the  $\phi$  shape. If it works out as expected, new CERES would be an excellent tool to study dramatic in-matter modification (rather than just enhancement or suppression) of vector resonances. It is also significantly statistics-limited experiment, deserving running time as much as possible.

## REFERENCES

1. R. Rapp, T. Schäfer, E. V. Shuryak and M. Velkovsky, Submitted to Ann.Phys. hep-ph/9904353.
2. See talks by K.Rajagopal and T.Schaefer, this volume.
3. D. Bailin and A. Love, Phys. Rep. 107, 325 (1984)
4. R. Rapp, T. Schäfer, E. V. Shuryak and M. Velkovsky, hep-ph/9711396; Phys.Rev.Lett., 81:53-56,1998; M. Alford, K. Rajagopal and F. Wilczek, hep-ph/9711395, Phys. Lett. **B422** 247 (1998).
5. M. Alford, K. Rajagopal and F. Wilczek, hep-ph/9804403, also talks by K. Rajagopal, this volume.
6. D.T. Son, Phys.Rev.D59:094019,1999;hep-ph/9812287
7. M.Stephanov, K.Rajagopal, E. Shuryak.Phys.Rev.Lett.81:4816-4819,1998; hep-ph/9806219 and 9903292, see also talks by K.Rajagopal and M.Stephanov this volume.
8. J.Cleymans, K. Redlich, nucl-th/9903063, and talk by J.Cleymans, this volume.
9. L.V. Bravina et al J.Phys.G25:351-361,1999, nucl-th/9810036, and the talk by L.Bravina, this volume.
10. See talk by U.Wiedemann, this volume.
11. E.Shuryak, Phys.Lett.B42 (1972) 357
12. L. Stodolsky, Phys. Rev. Lett. **75** (1995) 1044. E. V. Shuryak, Phys. Lett. **B423** (1998) 9.

13. G.Baym and H.Heiselberg, nucl-th/9905022
14. S. Mrowczynski, Phys.Lett.B (in press), nucl-th/9901078
15. E.Shuryak and O.V.Zhirov, Phys.Lett.89B (1979) 253
16. C. M. Hung and E.Shuryak, Phys.Rev.Lett. 75 (1995) 4003, Phys.Rev.C57:1891-1906,1998 and hep-ph/9709264; E.Shuryak, Proceedings of QM97, Nucl.Phys.A638 (1998) 207.
17. J.L. Nagle, B.S. Kumar, D. Kusnezov, H. Sorge, R. Mattiello, Phys.Rev.C53:367-376,1996
18. H. van Hecke, H. Sorge, N. Xu. Phys.Rev.Lett.81:5764-5767,1998 nucl-th/9804035
19. E.Shuryak, Sov.J. of Nucl. Phys. 16 (1972) 395; R. Venugopalan and M. Prakash, Nucl. Phys. **A546** (1992) 718.
20. J.Ollitrault Phys. Rev. **D46**, 229(1992); Phys. Rev. **D48**, 1132(1993), and talk at QM99.
21. H. Sorge, Phys. Rev. Lett. **78** 2309(1997) and **82** 2048 (1999)
22. P. Danielewicz et al Phys.Rev.Lett.81:2438-2441,1998: nucl-th/9803047 and talk by P.Danielewicz this volume.
23. L. Van Hove (CERN).Z.Phys.C21:93,1983
24. see talk by A.Poskanzer, this volume.
25. J.Stachel, (INPC 98, Paris), nucl-ex/9903007
26. D.Teaney and E.Shuryak, nucl-th/9904006.See also RHIC predictions, this volume.
27. J.Letessier and J.Rafelski, hep-ph/9807346
28. E.Shuryak, Phys.Lett.78B:150,1978 Sov. J. Nucl. Phys. 28, 408 (1978).
29. R. Rapp, G. Chanfray, J. Wambach, Nucl.Phys.A617:472-495,1997: hep-ph/9702210; talk by R.Rapp this volume.
30. R. Rapp and E.V.Shuryak, NA50 dileptons as QGP radiation, in progress.
31. J.I. Kapusta and E.Shuryak, Phys.Rev.D49:4694-4704,1994
32. C.M. Hung, E.V. Shuryak, Phys.Rev.C56:453-467,1997: hep-ph/9608299
33. G.Q. Li, C. Gale; Phys.Rev.Lett.81:1572-1575,1998: nucl-th/9805052
34. D.Lissauer and E.Shuryak, Phys.Lett.B 253 (1991) 15. M.Asakawa and C.M.Ko, Phys.Lett.B322 (1994) 33, D.Seiberg and C.Gale, Phys.Rev.C52 (1995) R490.
35. see talk of N.Willis, this volume.
36. H.Sorge, E.Shuryak, I.Zahed Phys.Rev.Lett.79:2775-2778,1997, hep-ph/9705329
37. M.Peskin,Nucl.Phys. B156 (1979) 365; D. Kharzeev and H. Satz, Nucl. Phys. A590, 515c,(1995)
38. T. Matsui and H. Satz, Phys. Lett. 178B, 416 (1986).
39. S.Gavin and R.Vogt, Phys.Rev.Lett.78:1006-1009,1997; D.E. Kahana and S.H. Kahana, nucl-th/9808025. Armesto, A. Capella, E.G. Ferreira Phys.Rev.C59:395-404,1999: hep-ph/9807258
40. E. Shuryak and D. Teaney, Phys.Lett.B430:37-42,1998
41. H.Heiselberg and R.Mattiello: nucl-th/990100
42. E. Shuryak,High energy collisions of strongly deformed nuclei: An old idea with few new twists, in progress.